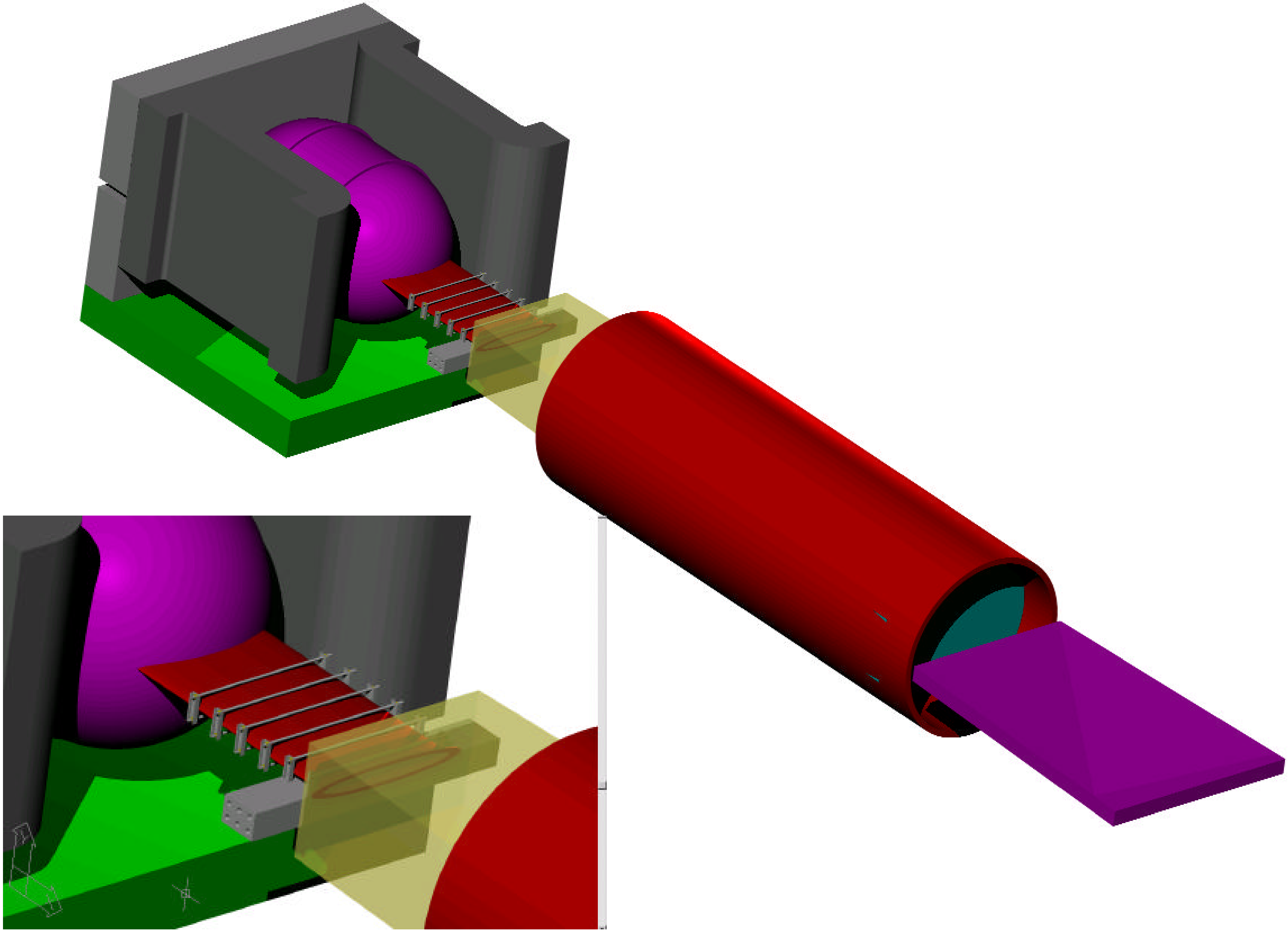
The Pursuit of $K_L \to p^0 u \overline{u}$



L. Littenberg - 10 Mar 2000

Outline

Motivation
- SM
- BSM

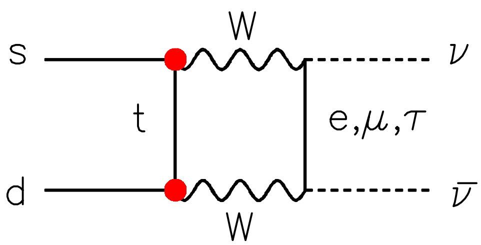
Experimental challenge
- Expect one decay in $33,000,000,000$
- Nothing in, nothing out

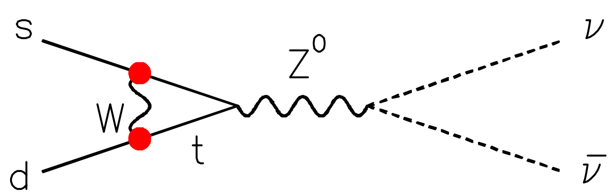
Present status
- Experiments
- Model-independent constraint

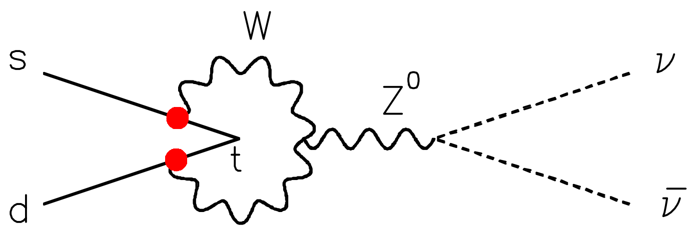
Competing plans
- KEK 391a
- KaMI

KOPIO
- Idea
- Implementation

$K_L \to \pi^o \nu \bar{\nu}$ in the Standard Model







$$B\left(K_L \to \pi^o \nu \bar{\nu}\right) \quad = \quad r_{K_L} \; \frac{\tau_{K_L}}{\tau_{K^+}} \; \frac{\alpha^2 B\left(K^+ \to \pi^o e^+ \nu\right)}{V_{us}^2 2\pi^2 sin^4\theta_W} \; \sum_l \left| Im V_{ts}^* V_{td} X\left(x_t\right) \right|^2$$

no. significant QCD corr.

$$= (3.1 \pm 1.3) \times 10^{-11} \quad \text{(recent CKM fit)}$$

r_{K_L} is correction of $B\left(Ke_3\right)$ for isospin, phase space, etc. $= 0.944$

Milestones in SM Calculation of $B(K_L \to \pi^0 \nu\bar{\nu})$

Gaillard & Lee '74 - Process CP-violating, $A \sim x ln x$ $\quad [x \equiv (m_q/m_W)^2]$

Kobayashi & Maskawa '73 - q could be t

Ellis, Gaillard & Nanopoulos '76 - $BR \sim 10^{-13}$ for $m_t \lesssim 4\text{GeV}$

Inami & Lim '80 - $A \sim x \left[\frac{2+x}{x-1} + \frac{3x-6}{(1-x)^2} ln x\right]$

Ellis, Gilman, Hagelin, others '83-89 - lowest order QCD corr. (v. small)

L.L. '88-89 - m_t getting big, $BR \sim 10^{-11}$!, ϵ effects v. small

Hagelin & L.L. '89 - long distance effects negligible

Buchalla & Buras '94 - NLLA QCD corrections (uncertainty tiny)

Marciano & Parsa '95 - Corrections to hadronic m.e. ($\leq 10\%$)

Buchalla & Buras '97 - Two loop large m_t EW corrections (small)

Buchalla & Isidori '98 - CP-even contribution $\sim 10^{-4}$

Bottom line:

$B\left(K_L \to \pi^0 \nu\bar{\nu}\right)$ is extremely well-determined in the SM

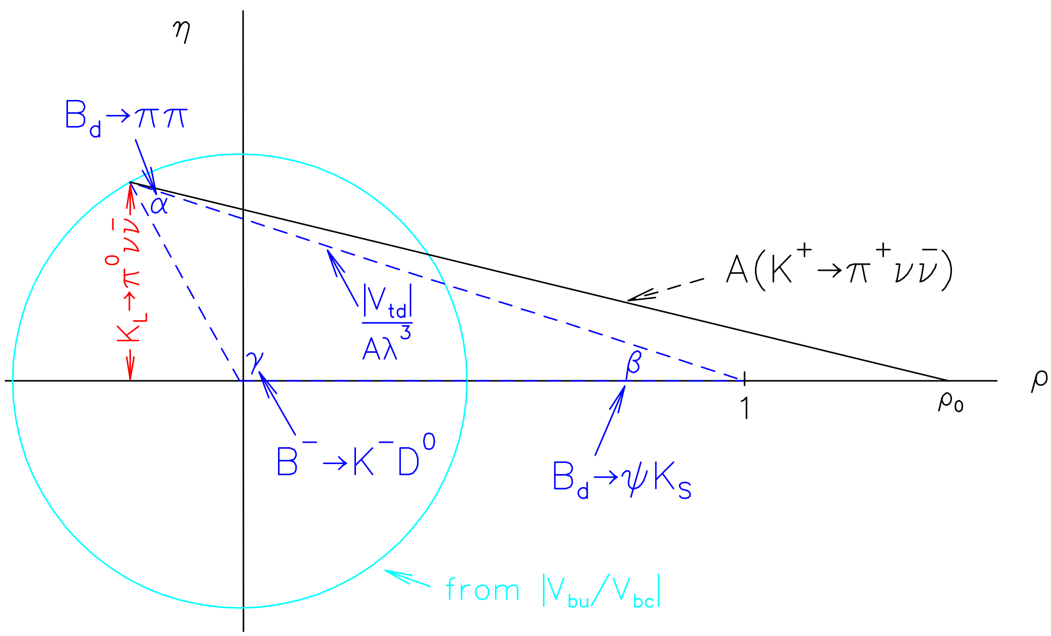
$K_L \rightarrow \pi^0 \nu\bar{\nu}$ in the Standard Model

Pure direct CP-violating (state-mixing very small)

Calculation in terms of fundamental parameters good to $\lesssim 2\%$

In terms of usual unitarity triangle parameterization:

$$B(K_L \rightarrow \pi^0 \nu\bar{\nu}) = 4 \cdot 10^{-10} A^4 \eta^2$$



Gives height of UT without triangulation

- with $K^+ \rightarrow \pi^+ \nu\bar{\nu}$ can determine ρ as well

Also note that

$$B(K_L \rightarrow \pi^0 \nu\bar{\nu}) = 1.56 \cdot 10^{-4} [Im(V_{ts}^* V_{td})]^2 \equiv 1.56 \cdot 10^{-4} [Im\lambda_t]^2$$

$Im\lambda_t$ presently triangulated to $\sim 22\%$,

- KOPIO could directly measure it to $7 - 8\%$

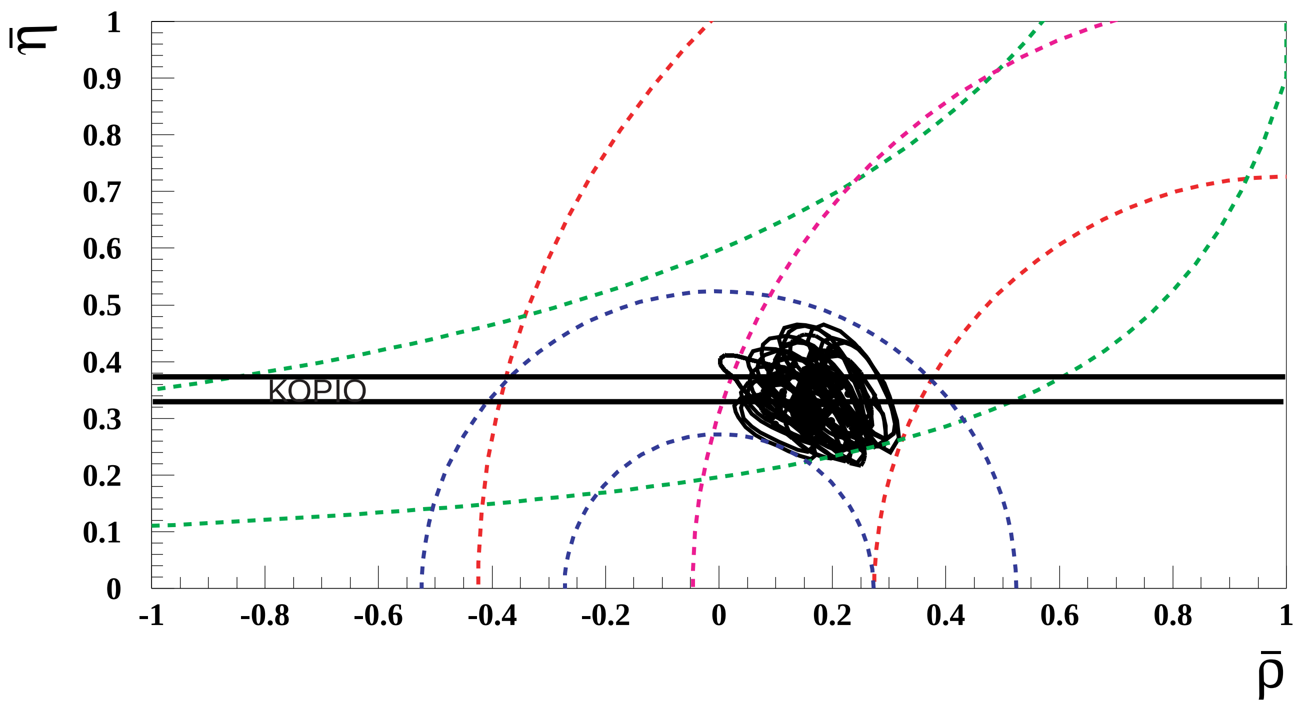
There are only a few solid measurements on the UP

- none is better!

Potential of KOPIO in SM CKM fits

Plot from Plaszczynski and Schune (hep-ph/9911280)
- conservative fit to present CKM data

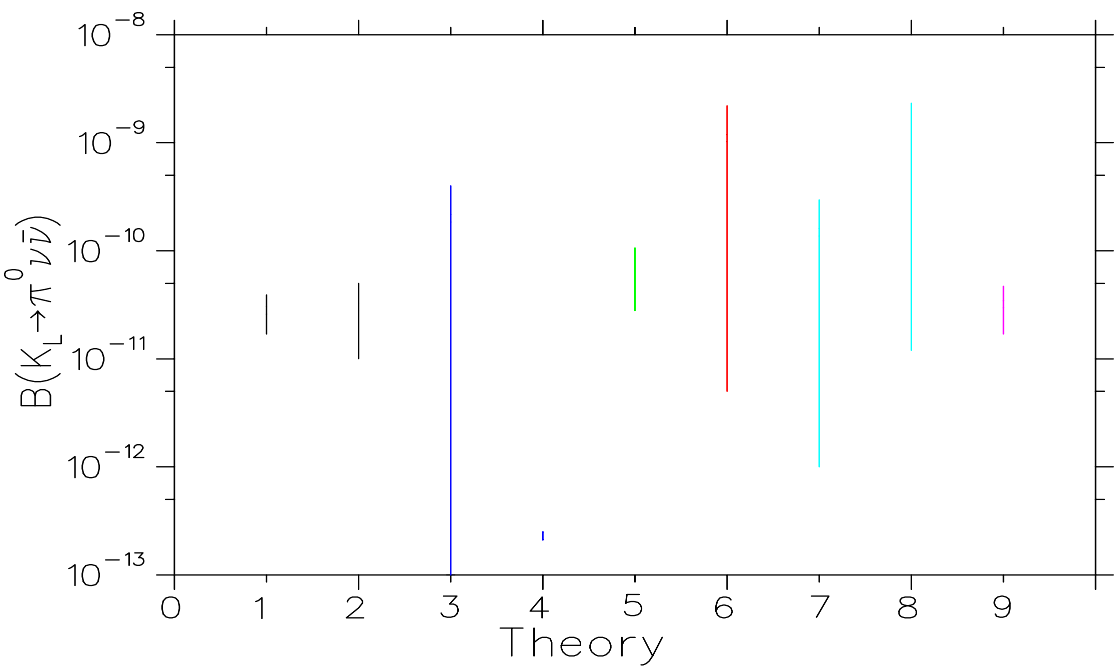
Expected KOPIO result superimposed
(assumes errors on A and m_t not limiting)



$K_L \to \pi^0 \nu \bar{\nu}$ Beyond the Standard Model

	Who	What	$10^{11} B(K_L \to \pi^0 \nu \bar{\nu})$
1	Buchalla	Standard Model CKM fit	2.8 ± 1.1
2	Plaszczynski/Schune	Conservative SM fit	$1 - 5$
3	Buras, *et al.*	SUSY	$0 - 40$
4	Brhlik, *et al.*	all CP-viol. due to SUSY	$\sim .023$
5	Chanowitz	$SU(2)_L \times SU(2)_R$ Higgs	$2.8 - 10.6$
6	Hattori, *et al.*	4th generation	$0.5 - 220$
7	Xiao, *et al.*	top-color assisted technicolor	$0.1 - 29.5$
8	Xiao, *et al.*	multiscale walking technicolor	$1.2 - 233$
9	Kiyo, *et al.*	seesaw L-R model†	$(1 - 1.2)\times$ SM

† predicts spectrum will be altered.



An interesting example

hep-ph/9909480

"Can Supersymmetry Soft Phases Be the Source of All CP Violation?"

— M. Brhlik, L. Everett, G.L. Kane, S.F. King, O. Lebedev

They can account for all present data with a real CKM matrix.

ϵ and ϵ' come from gluino-squark diagrams.

CP-violation in the B-system is essentially superweak!

Predictions:

Neutron & electron EDM not enhanced

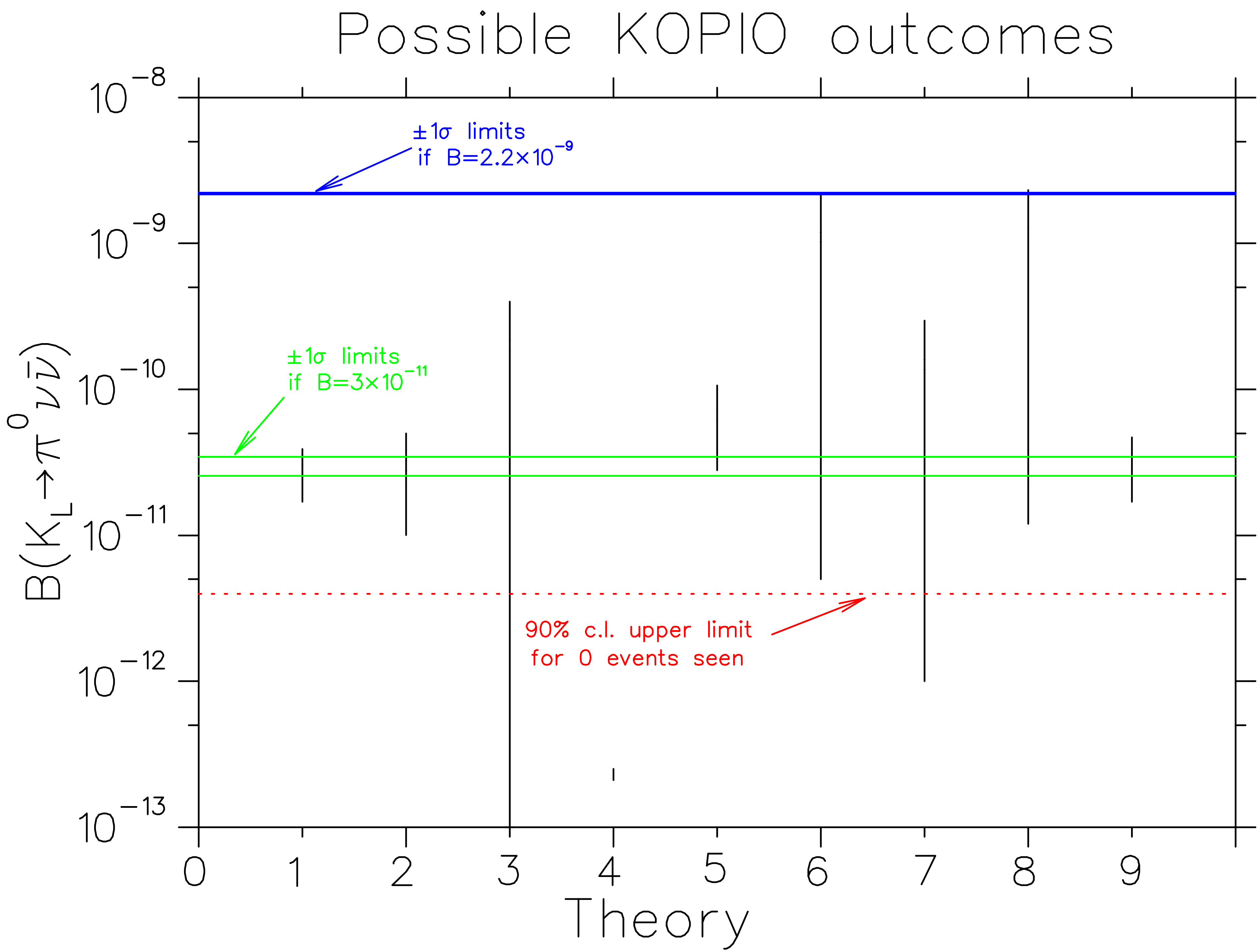
$\sin 2\beta = -\sin 2\alpha$ (latter not easy to measure)

CP-asymmetry in $b \to s\gamma$ **may** be enhanced

$\bar{D} - D$ mixing **may** be enhanced (but no CP-violation)

BUT

$B(K_L \to \pi^0 \nu\bar{\nu})/B(K^+ \to \pi^+ \nu\bar{\nu}) \sim \epsilon$ (instead of ~ 0.4).



Possible KOPIO outcomes
±1σ limits
if B=2.2×10^-9
±1σ limits
if B=3×10^-11
90% c.l. upper limit
for 0 events seen
B(K_L→π^0 νν̄)
10^-8
10^-9
10^-10
10^-11
10^-12
10^-13
0
1
2
3
4
5
6
7
8
9
Theory

Why Only Now?

It was only realized in 1988 that top quark must be heavy enough for $B\left(K_L \to \pi^0 \nu\bar{\nu}\right)$ to be detectable.

It's a long way to the Standard Model level, and even most BSM possibilities tend to be of the same order as those in $K^+ \to \pi^+ \nu\bar{\nu}$.

The signature is rather challenging:

- Both the initial and final states are neutral.
- There are 3 bodies in the final state, of which 2 are undetectable.
- The one detectable particle is a common product of K decay and can also easily arise from other sources in the beam, such as hyperon decay or neutron interaction with residual gas.
- The main background, $K_L \to \pi^0\pi^0$, is $30,000,000$ times more common than the signal.

Only in the 1990's was a source available that would allow K decays with 10^{-11} branching ratios to be measured.

Only in the 1990's were techniques capable of adequately coping with the high rates proven (E865, E871).

Only in the late 1990's were the photon vetoing and analysis techniques needed for this experiment proven (E787).

It wasn't realized until 1995 that there existed a practical method for microbunching the slow extracted beam at high intensity.

The challenge of KOPIO

Expected branching ratio 3×10^{-11}

No charged particles in or out
- no visible vertex

2/3 of final state unobservable
- no kinematic constraints

$K_L \to \pi^0\pi^0$ background $30,000,000\times$ larger
- little distinction in p_T dist. between it & signal
- very effective vetoing required

Other K decays can also be dangerous

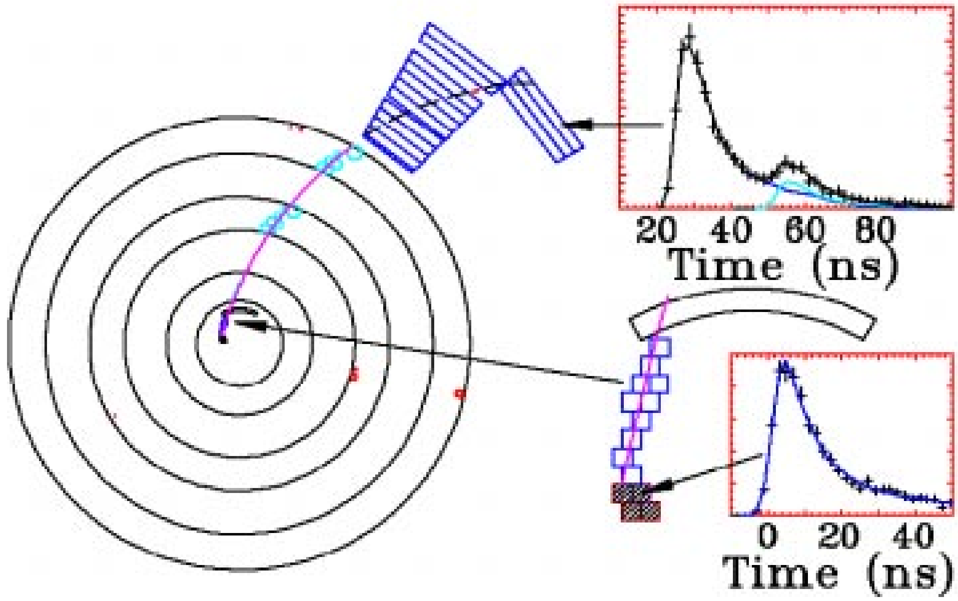
Background from neutron-produced π^0's, η's
- requires vacuum of 10^{-7}

Background from hyperon decay π^0's

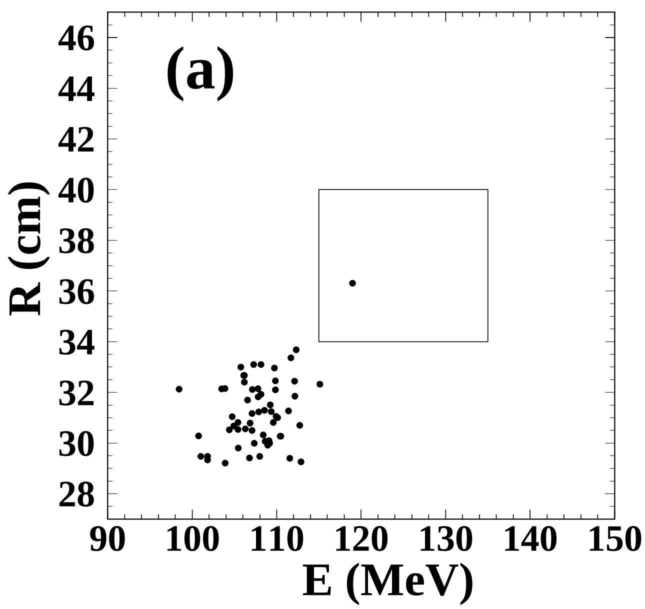
Background from random γ's

Present status: $B(K_L \to \pi^0\nu\bar{\nu}) < 5.9 \times 10^{-7}$
- from KTeV, using Dalitz-converted π^0's

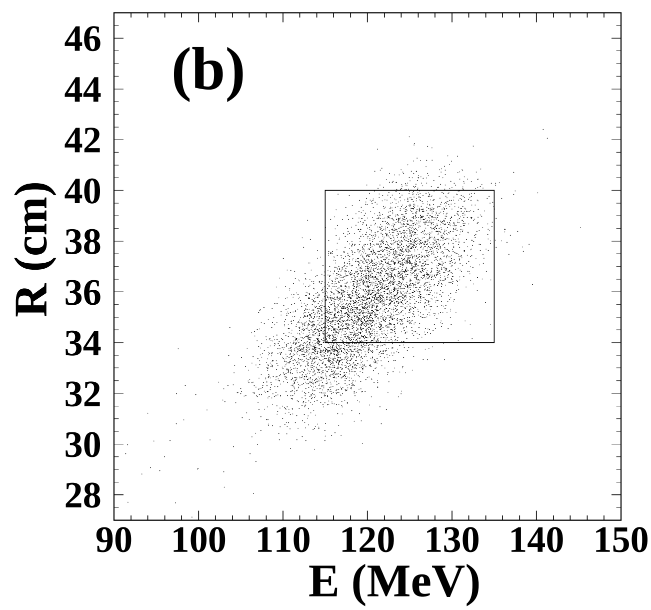
$K^+ \to \pi^+ \nu \bar{\nu}$ event



Data

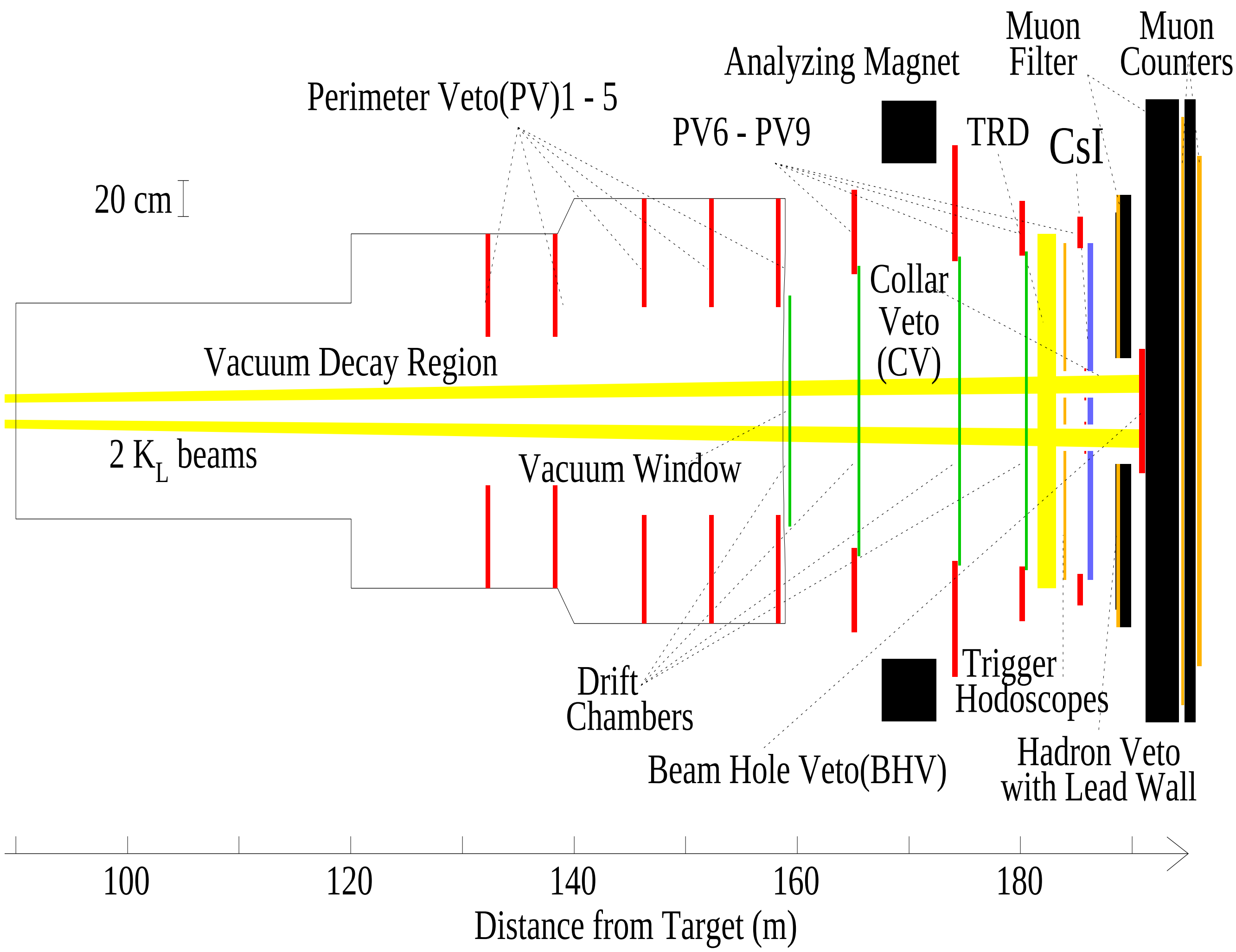


Monte Carlo



- Probability for the event to be one of the known backgrounds is very low.

E799-II (KTeV) Detector



KTeV $K_L \to \pi^0 \nu\bar{\nu}$ using $\pi^0 \to e^+e^-\gamma$

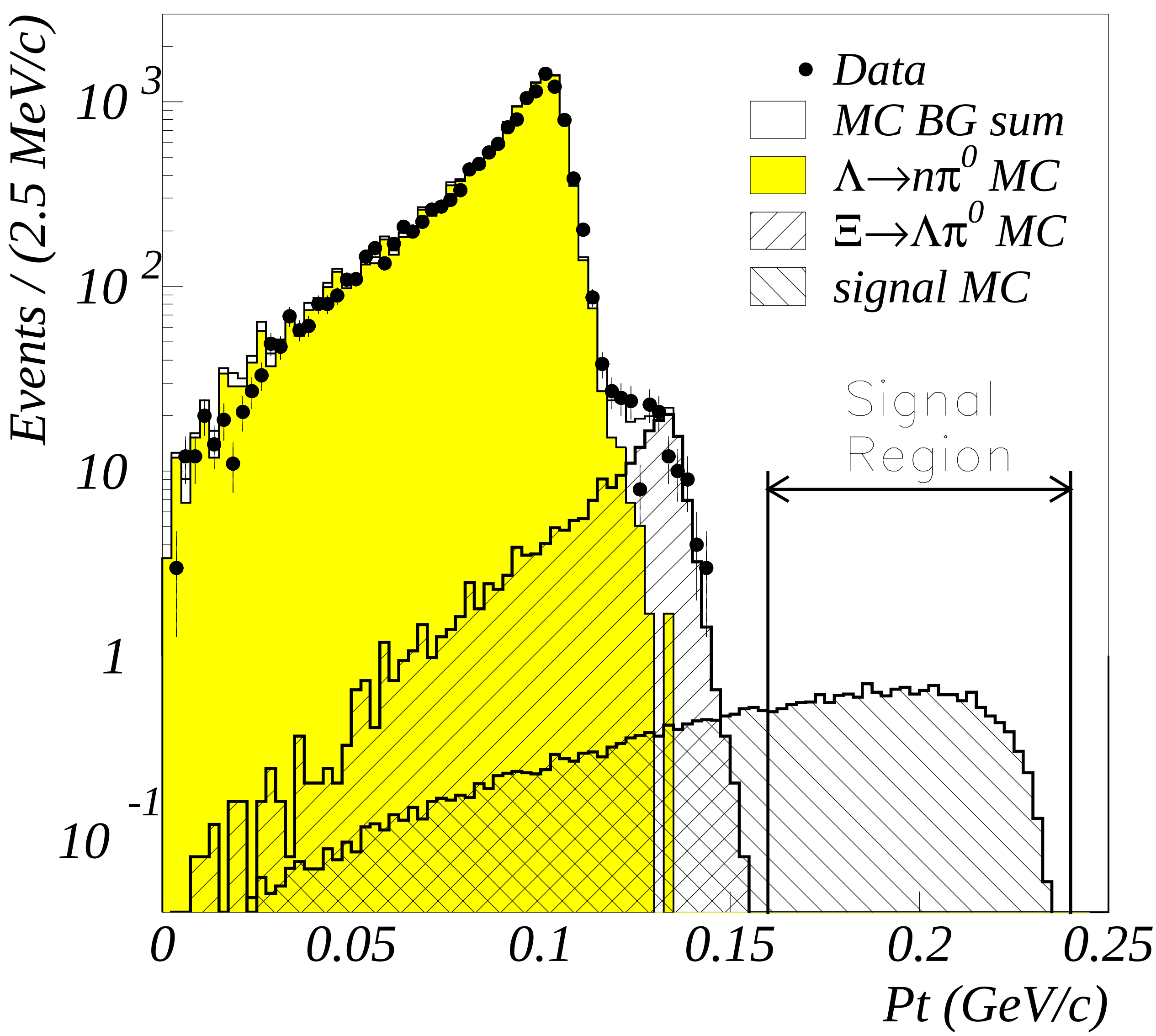
To be published in PRD (hep-ex/9907014).

Technique allows a vertex to be determined.

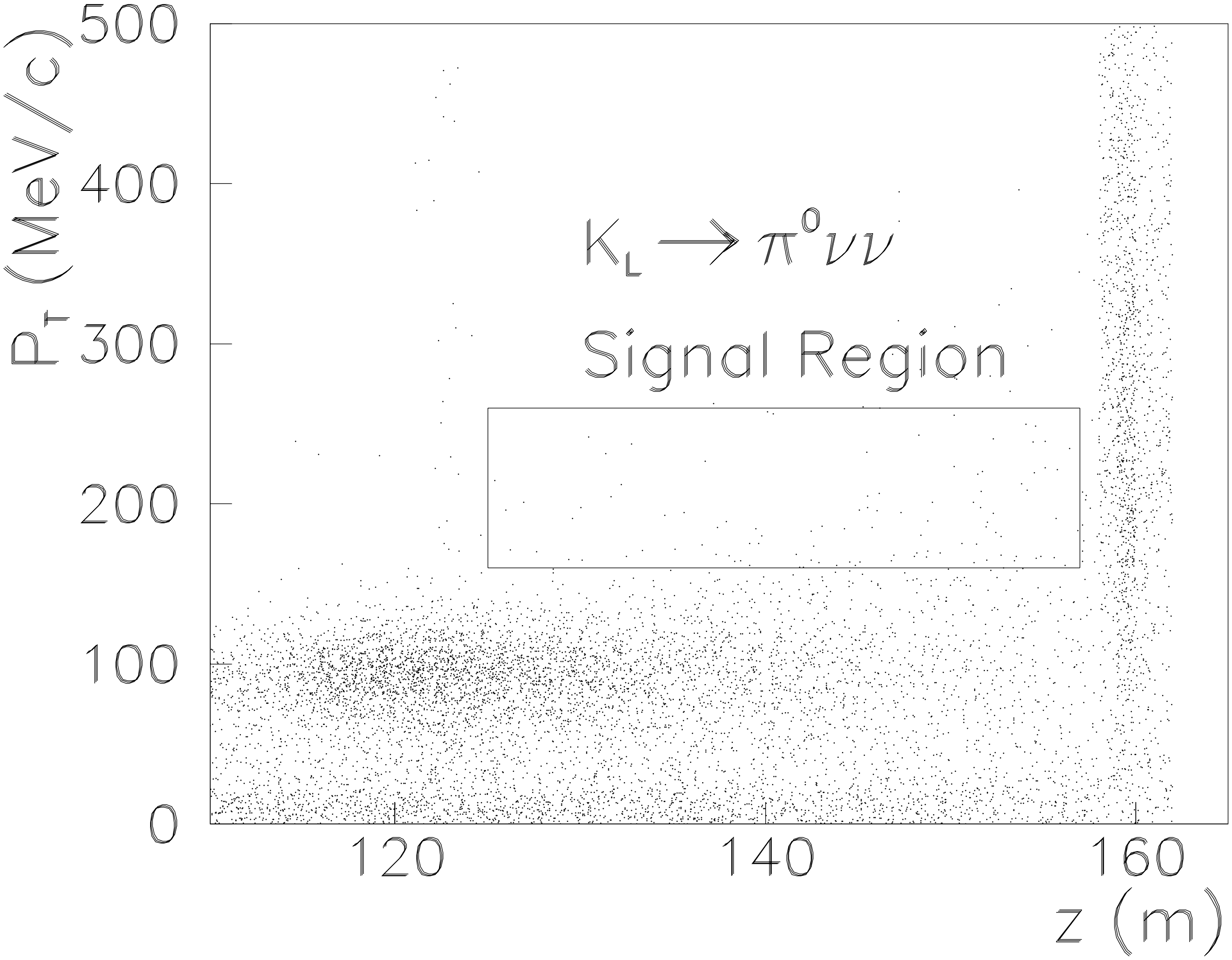
No events observed, $B\left(K_L \to \pi^0\nu\bar{\nu}\right) < 5.9 \times 10^{-7}$ at 90% c.l.

Calculated background 0.04 events.

Estimate of ultimate reach $\sim 10^{-9}$.



FNAL E799 Search for $K_L \to \pi^0\nu\bar{\nu}$



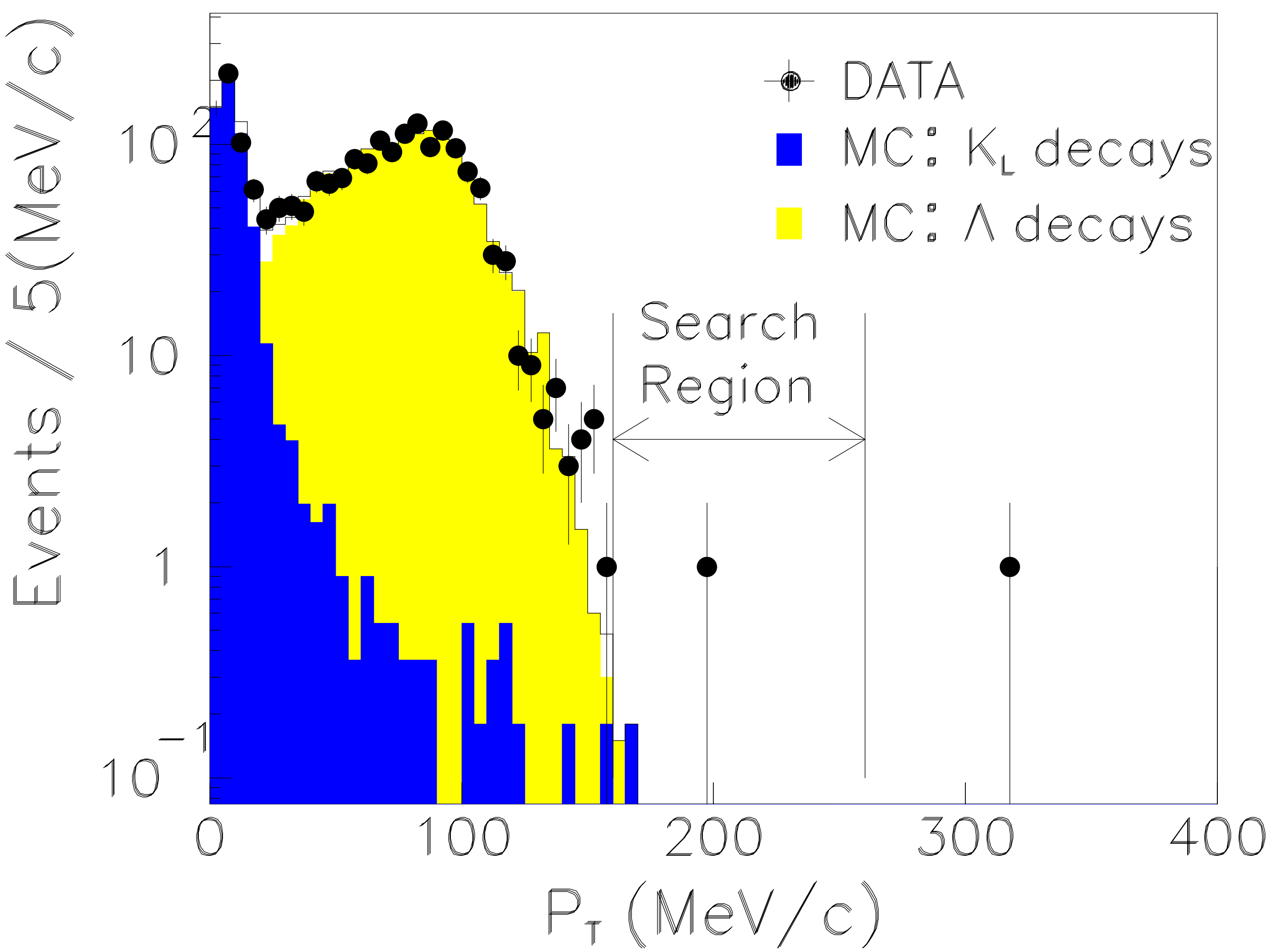
p_T vs z_V for single-π^0 events

Band at $z_V \approx 160\,\mathrm{m}$ due to n ints. in vacuum window

Band near $p_T = 100\,\mathrm{MeV/c}$ due to $\Lambda \to n\pi^0$

Events with $p_T \approx 0$ due to $K_L \to \gamma\gamma$

FNAL E799 Search for $K_L \to \pi^0 \nu \bar{\nu}$



Result of one-day run in special configuration.

P_T distribution with all other cuts
- calculated backgrounds overlaid.

Residual background consistent with neutron interactions

Yields $B\left(K_L \to \pi^0 \nu \bar{\nu}\right) < 1.6 \times 10^{-6}$ at 90% c.l.

A Model Independent Limit on $B(K_L \to \pi^0 \nu\bar{\nu})$

$B\left(K_L \to \pi^0 \nu\bar{\nu}\right) < 4.4 \times B\left(K^+ \to \pi^+ \nu\bar{\nu}\right)$

Proposed by Y. Grossman & Y. Nir

- Phys. Lett. **B398**, 163 (1007)

A consequence of $\Delta I = \frac{1}{2}$ rule

- trivial in SM

- true in for almost any short-distance interaction
  even if that interaction conserves CP

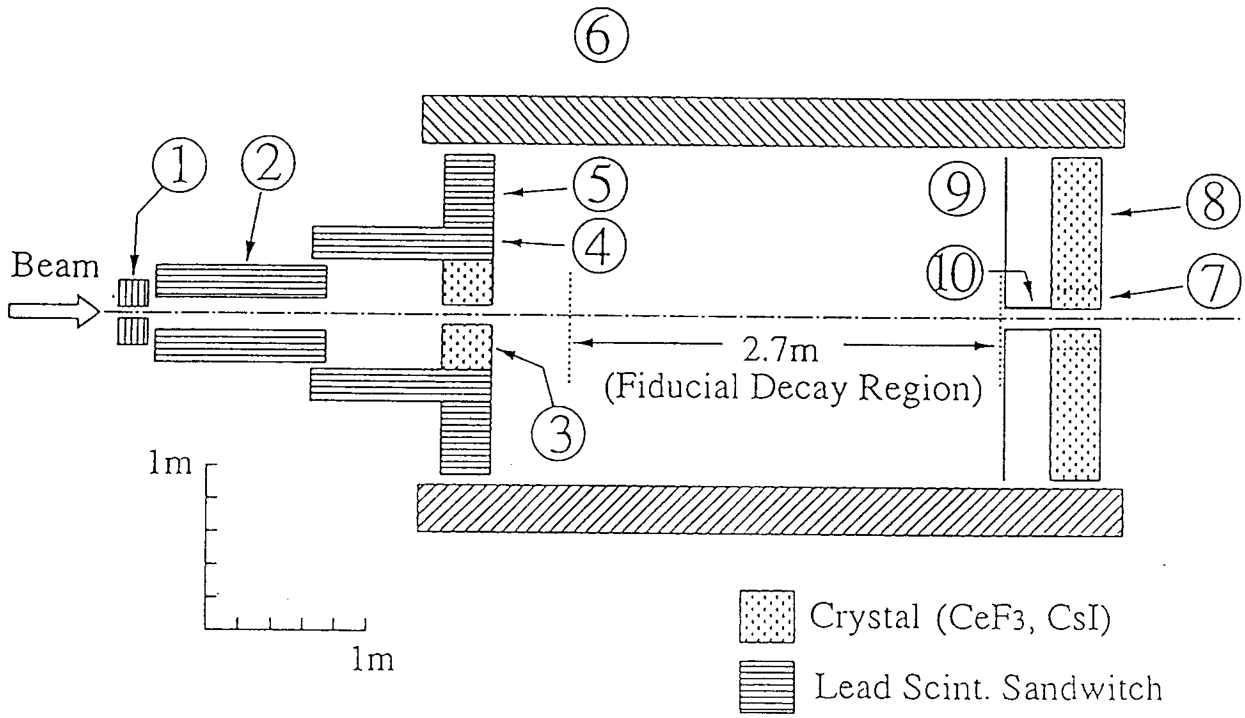
New E787 result is $B\left(K^+ \to \pi^+ \nu\bar{\nu}\right) = \left(1.5^{+3.4}_{-1.2}\right) \times 10^{-10}$

This leads to $B\left(K_L \to \pi^0 \nu\bar{\nu}\right) < 3.1 \times 10^{-9}$ at 95% c.l.

Far better than any other current limit

- but still 100 times larger than SM expectation

KEK E391a search for $K_L \to \pi^0 \nu \bar{\nu}$



Carefully designed "pencil" beam, compact detector

Entire apparatus in vacuum

Very high performance photon veto

Expected to reach $\sim 10^{-10}$ single event sensitivity
- *i.e.* $\sim 3\times$ S.M. prediction

Beamline construction & tuning in November 1999

Run start scheduled for 2001

Test bed for JHF experiment

KaMI $K_L \to \pi^0 \nu \bar{\nu}$

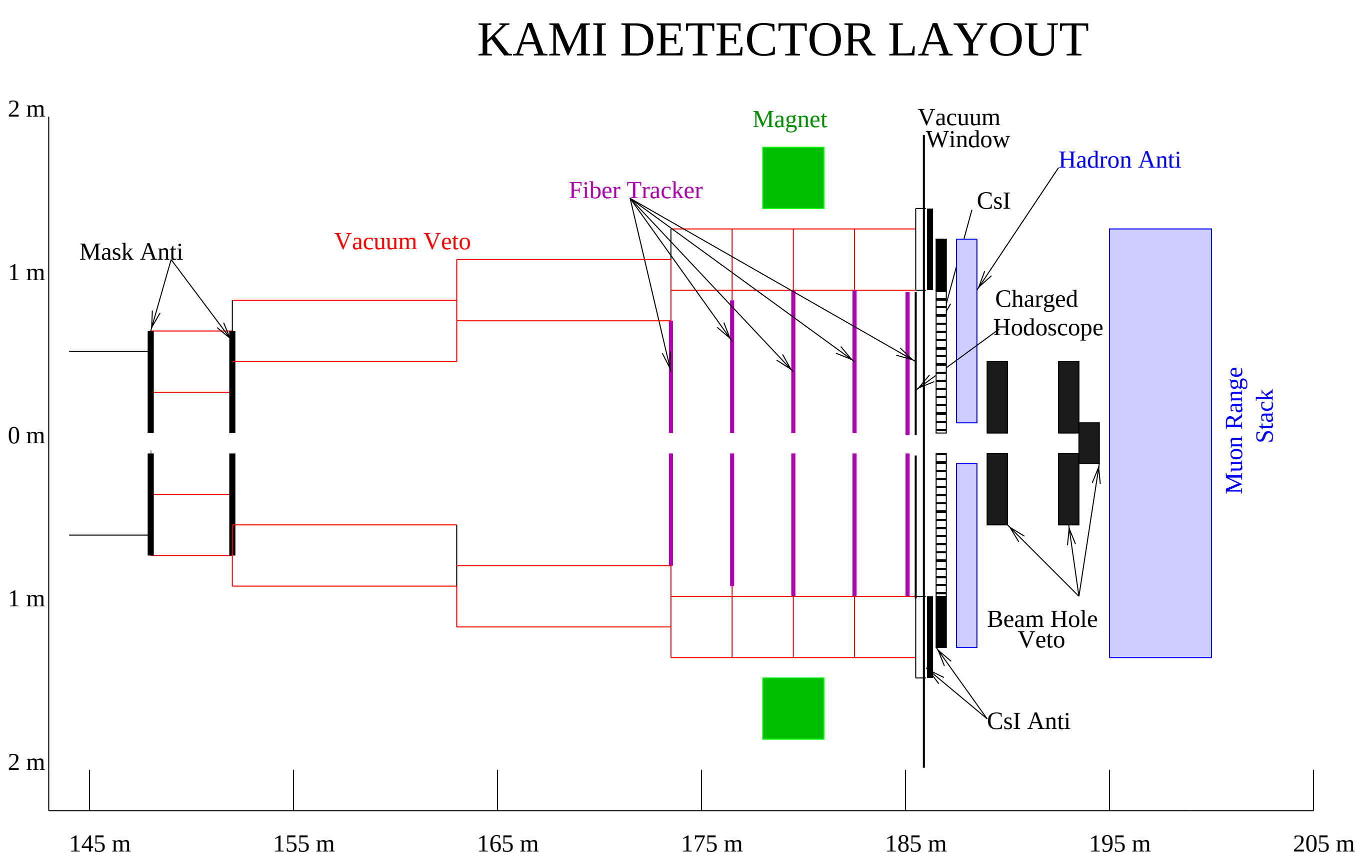
EOI (hep-ex/9709026), no proposal yet.

3×10^{13}/spill, 120 GeV proton beam at Main Injector.

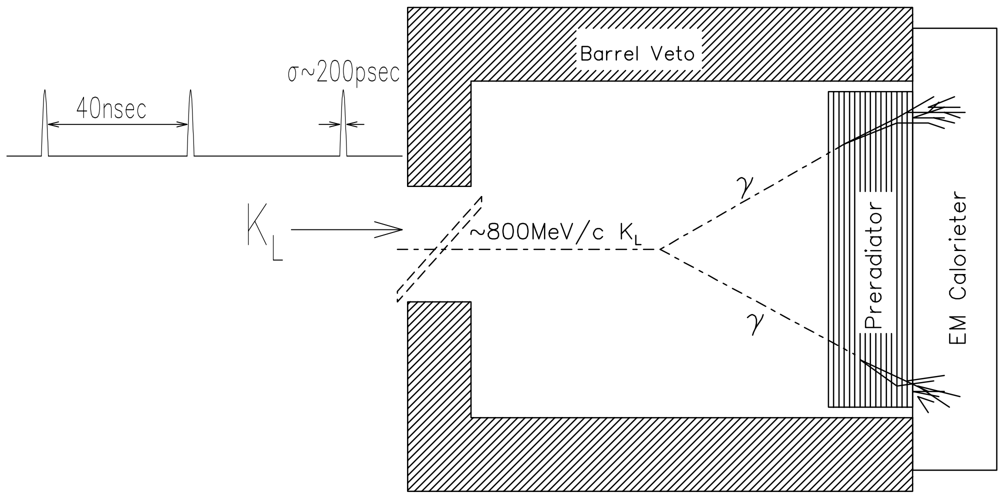
Pencil beam, $\pi^0 \to \gamma\gamma$ decay

Recycled KTeV CsI array central

Eventually ~ 100 events, S:B $\sim 3:1$



Principles of KOPIO



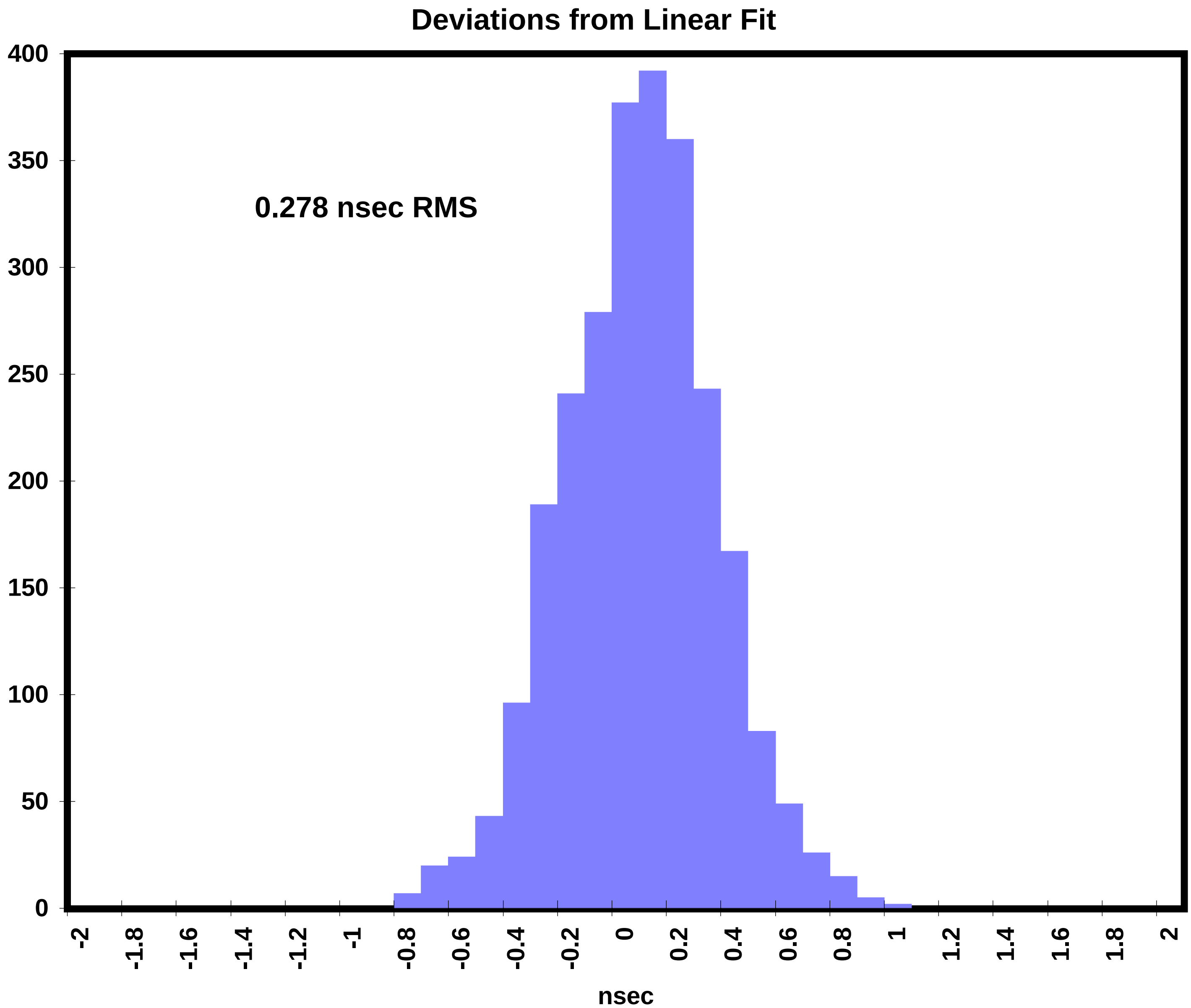
Work in the K_L center of mass system
All possible initial & final state quantities measured
Measure backgrounds
Veto hermetically

Microbunched, large angle (low energy) beam
Preradiator to measure γ directions
+ calorimeter, get energies, times
E787-type veto + beam catcher veto

Advantages:

- vertex positively determined
- 4C fit to π^0
- can require π^0 consistent with $K_L \to \pi^0 \nu\bar{\nu}$
- can avoid configuration with low energy missed γ's
- reduced bckgnd from K_L decay & other sources
- most neutrons, off-momentum K_L put out of time
- most n below π^0 production threshold
- no hyperons
- preradiator also serves as particle ID device

Test of microbunching on extraction at AGS



Technique now well established

Very successfully used to smooth AGS spill

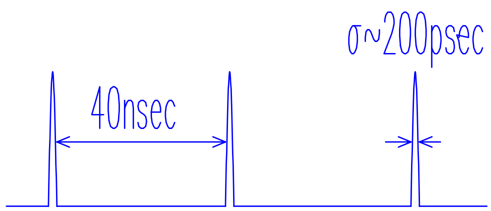
The neutral beam

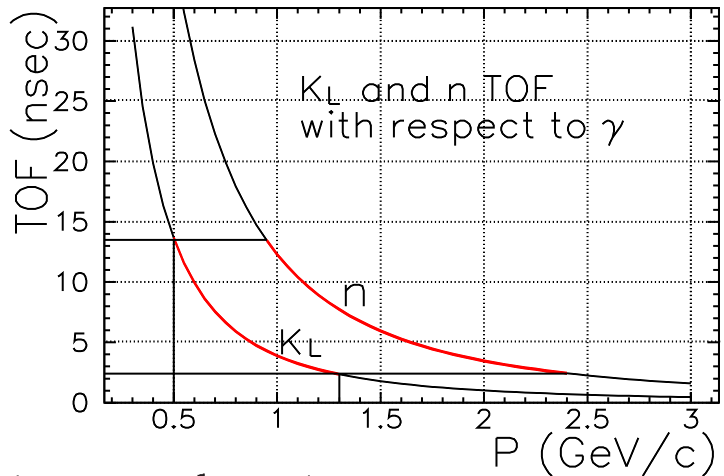
1. Use low energy bunched K_L beam

- Momentum of K_L by Time of Flight

  $\sigma_t \sim 200psec \Rightarrow \Delta P/P \sim$ a few %

  Rejecting $K_L \to \pi^0\pi^0$ peak in the K_L CM system.

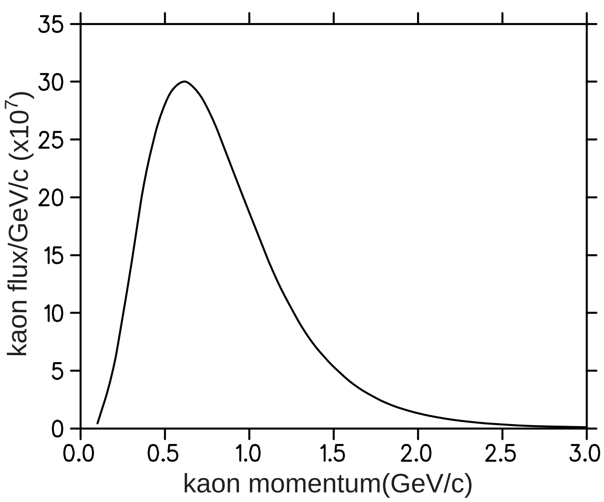


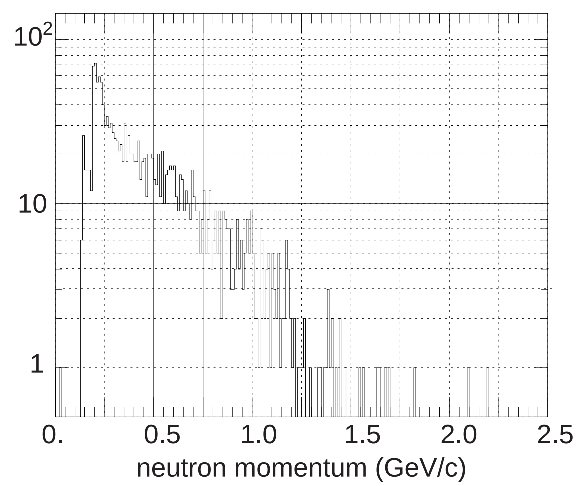


- Neutrons and photons arrive at other times

  High rate capability

  Suppress backgrounds (e.g. Accidentals, $nA \to \pi^0 nA$)





- Background beams are at low energy

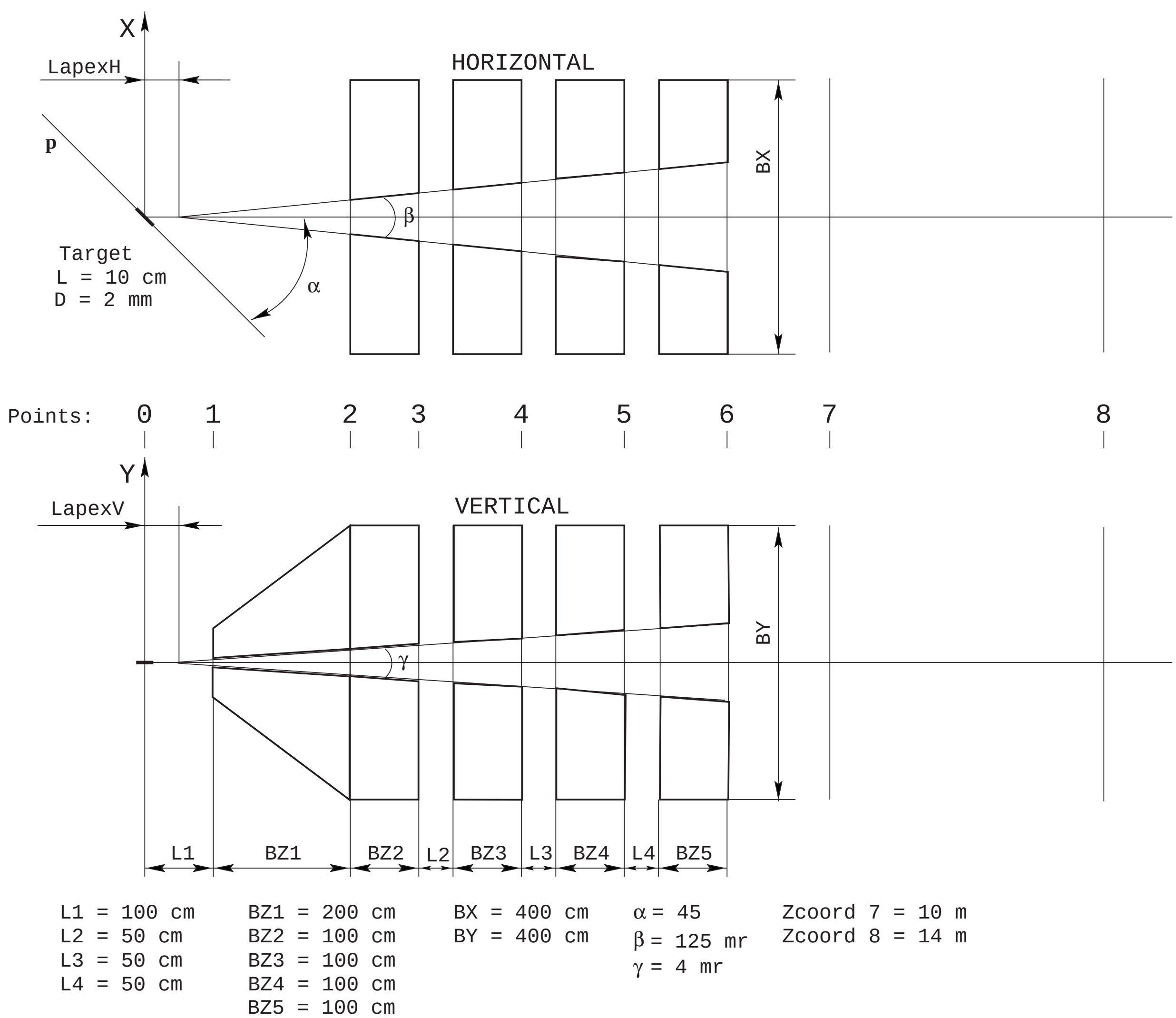
  Hyperons (Λ, Ξ) decay before reaching the decay volume

  Neutrons mostly below π production threshold $\Rightarrow$ Good K_L/n ratio

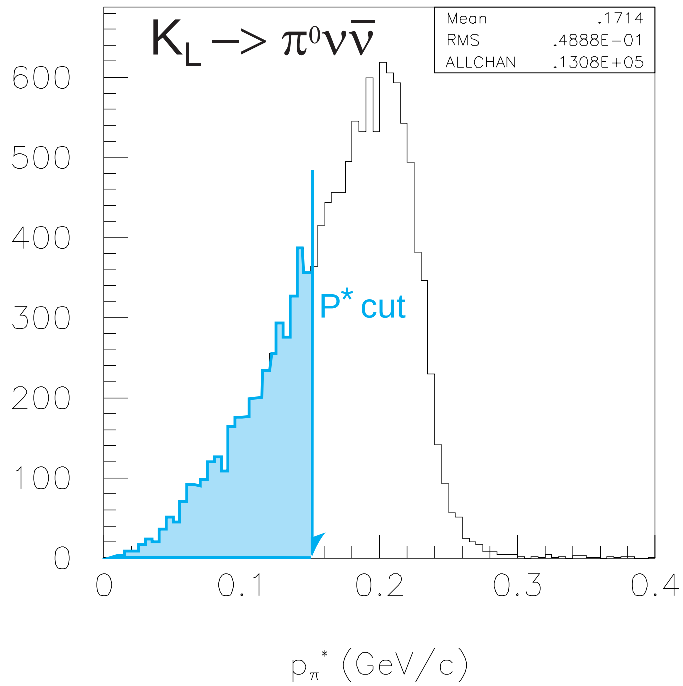
  Good collimation

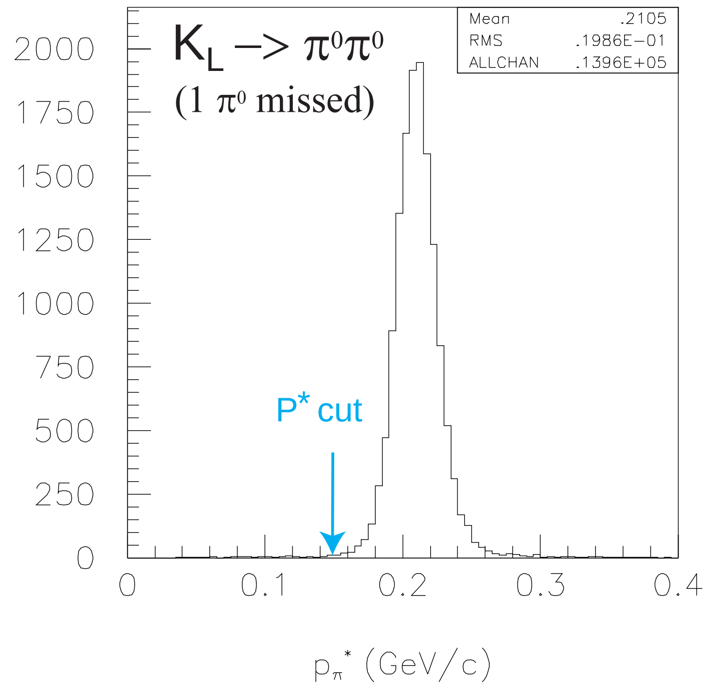
KOPIO Beam

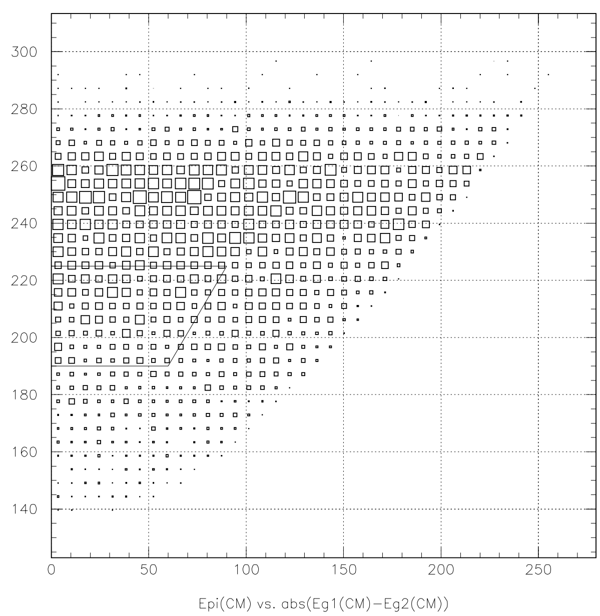
Microbunched at 25 MHz (< 200ps bunches)
To get K_L slow enough to do TOF, go to 40^o
To get enough K_L need 100 TP/spill
Gives 2.6×10^8 K_L, of which 4.2×10^7 decay usefully
But 10^{11} neutrons, luckily mainly very low energy
Need to reduce beam halo to 10^{-4} of in-beam value
For clean conditions accept only 1-decay μ-bunches
Optimization gives 3-second spill length

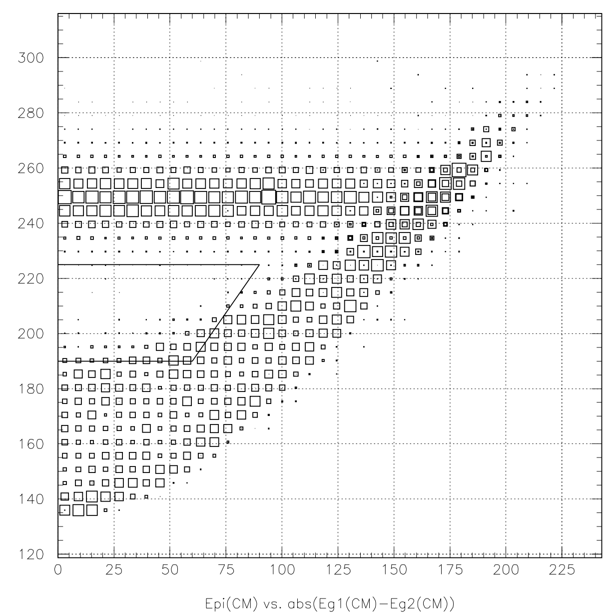


K_L -> $\pi^0\nu\bar{\nu}$ and K_L -> $\pi^0\pi^0$ identification

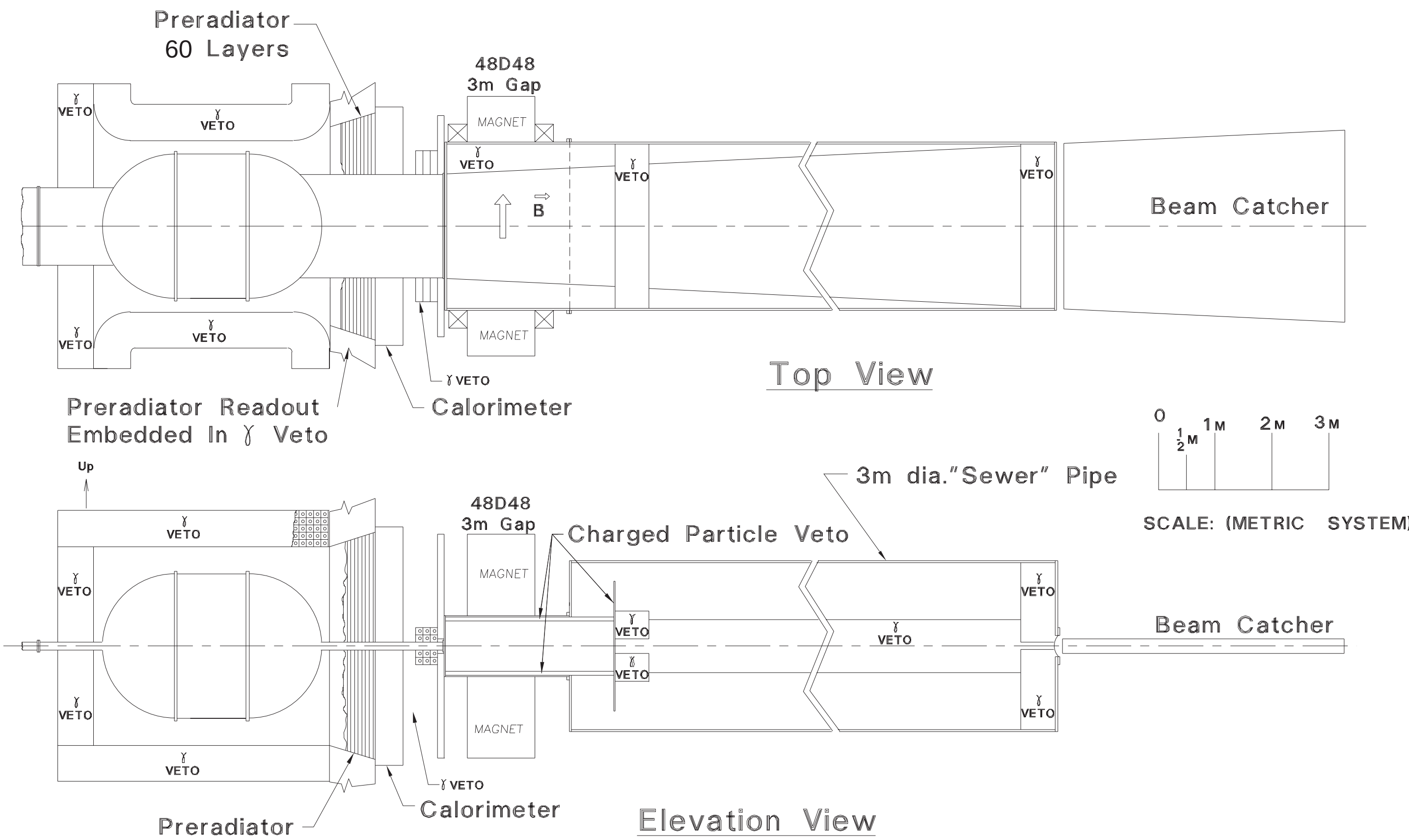


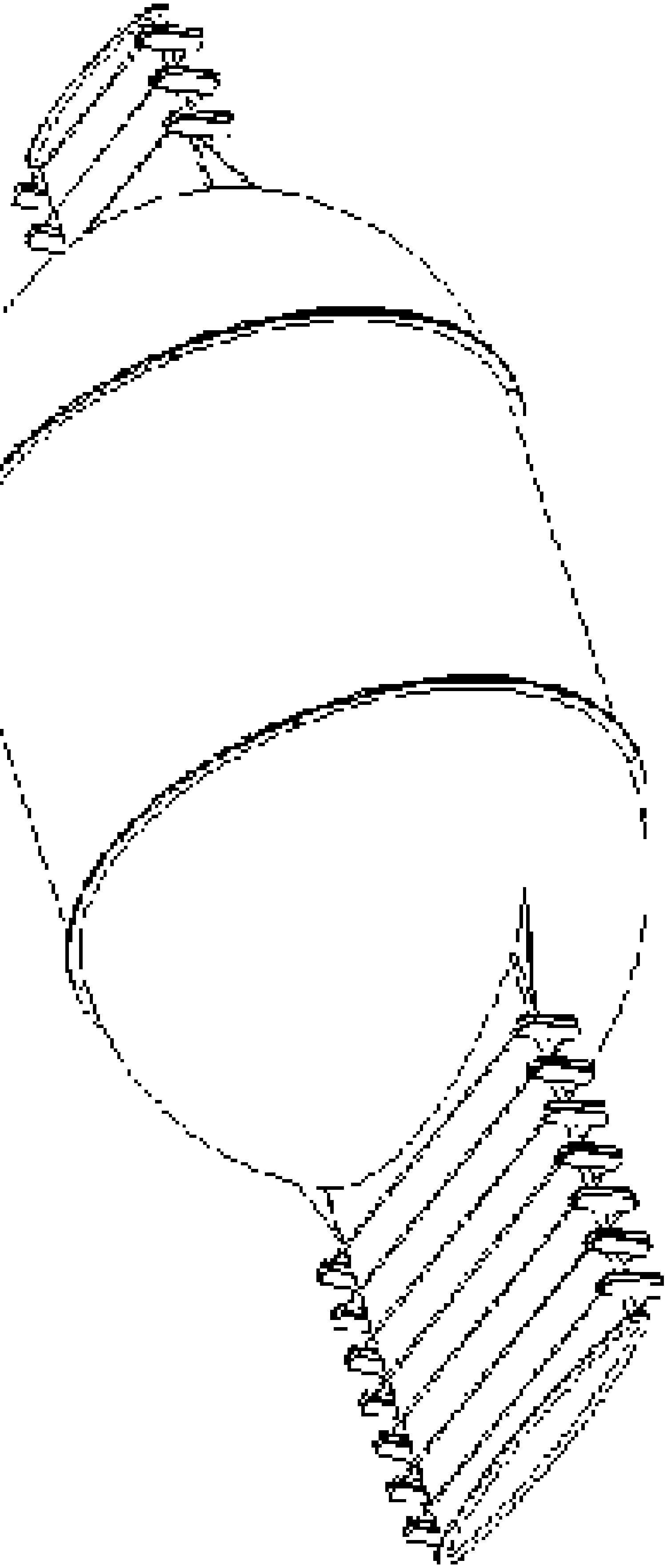






KOPIO Apparatus Schematic



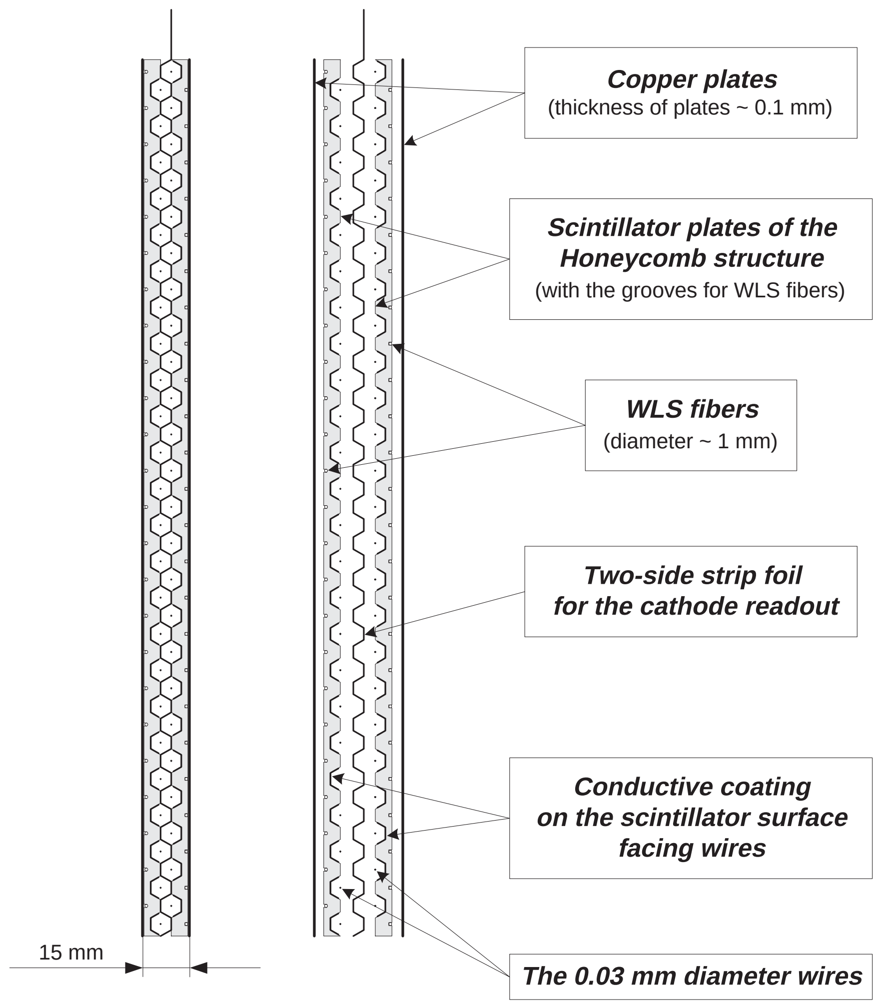


Preradiator - type A

Allows vertex to be determined

Need ~ 25mr resolution, w/o spoiling σ_{k_γ}

Two designs being prototyped



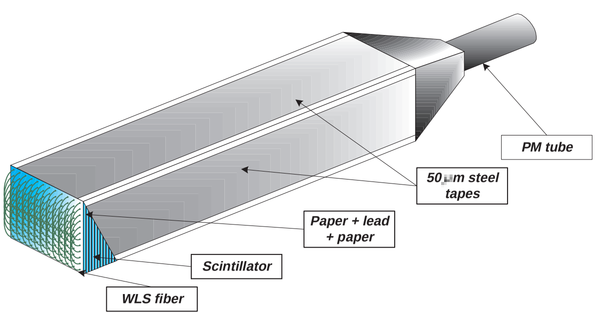
Calorimeter

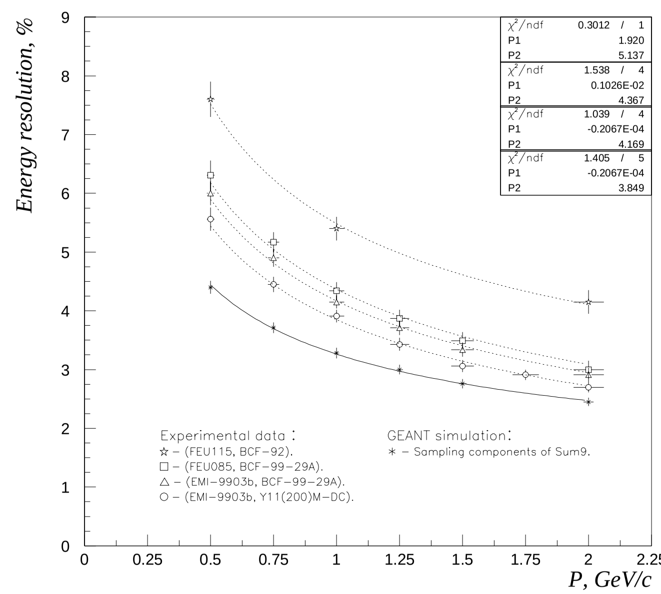
Need $\sigma_E/E \propto 0.03/\sqrt{E}$

Use well-understood shashlik technology

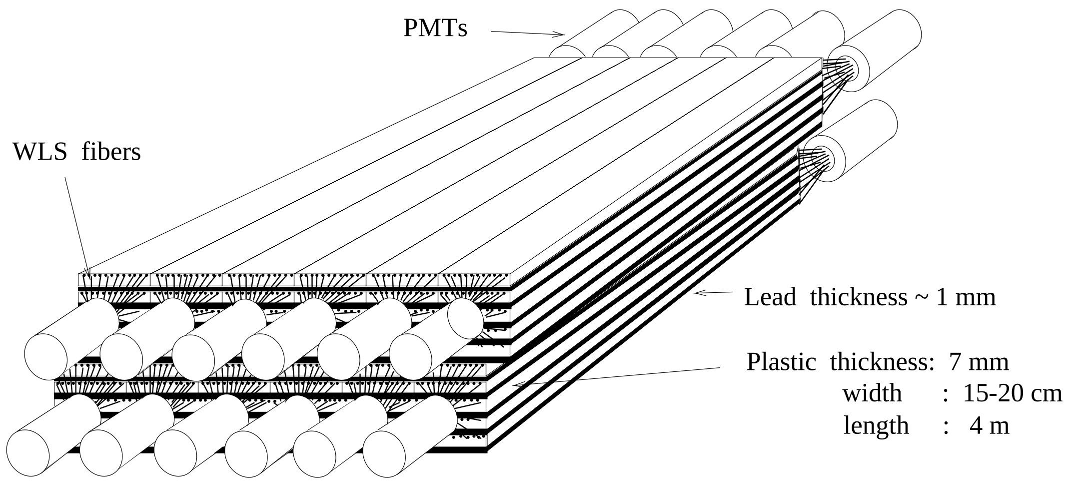
Better than $0.04/\sqrt{E}$ already demonstrated

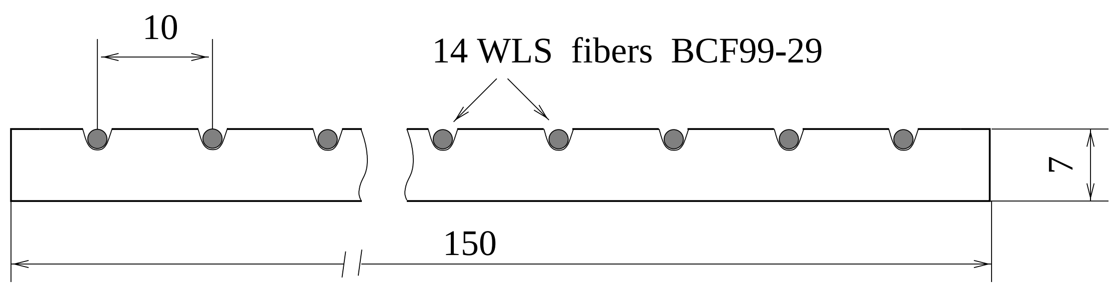
MC indicates goal can be straightforwardly reached

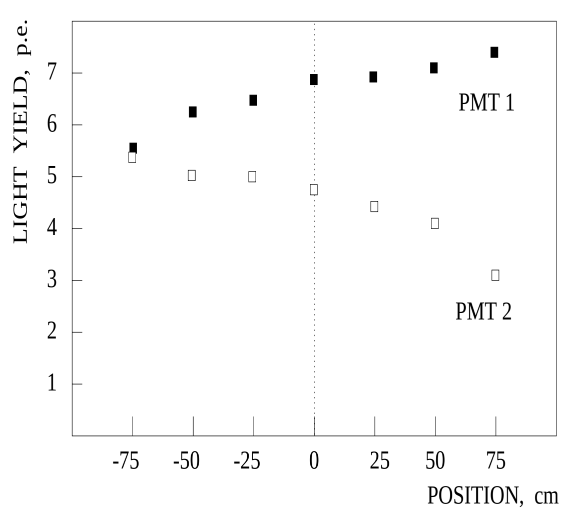


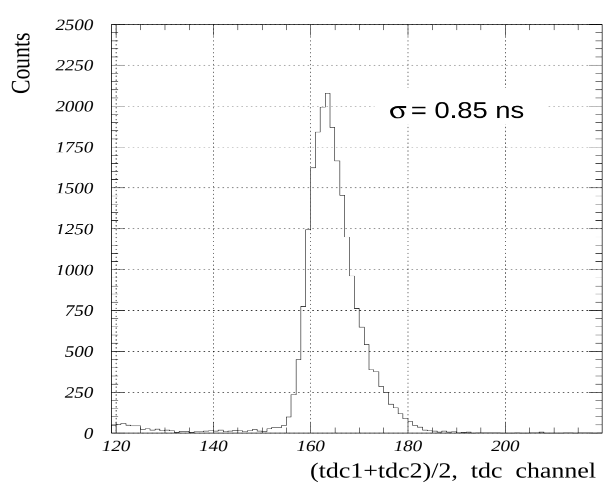


E926 Photon Veto









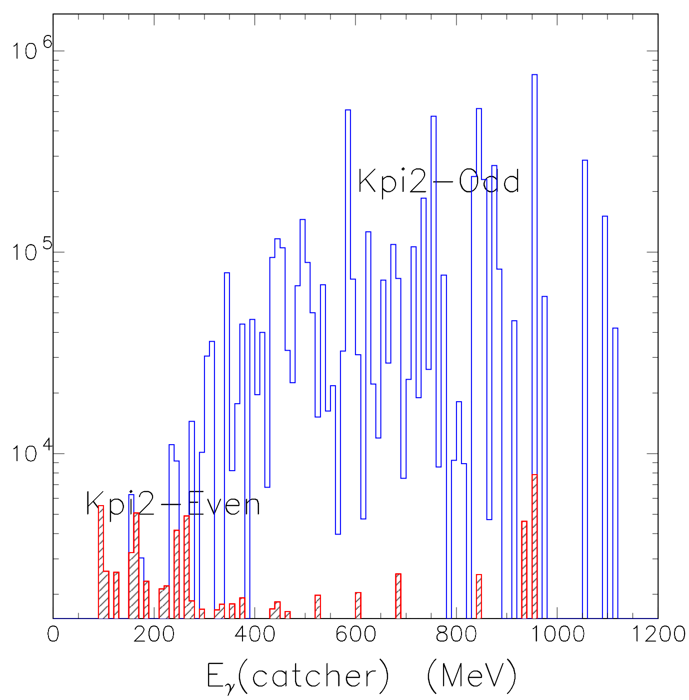
Demands on the KOPIO Beam Catcher

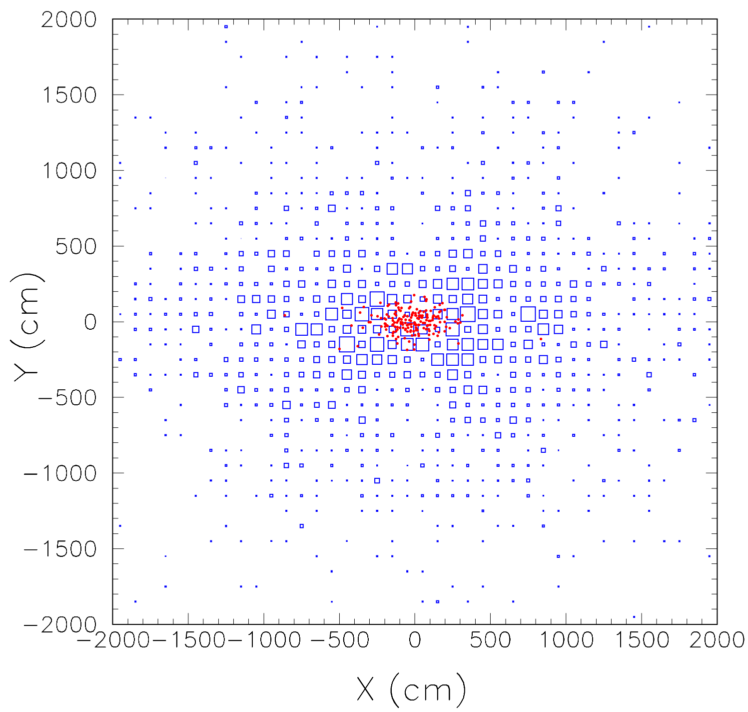
Not easy to veto γ's in flux of 3×10^{10} Hz of neutrons

Aerogel insensitive to large majority of neutrons
- Demand hits in 3 successive layers

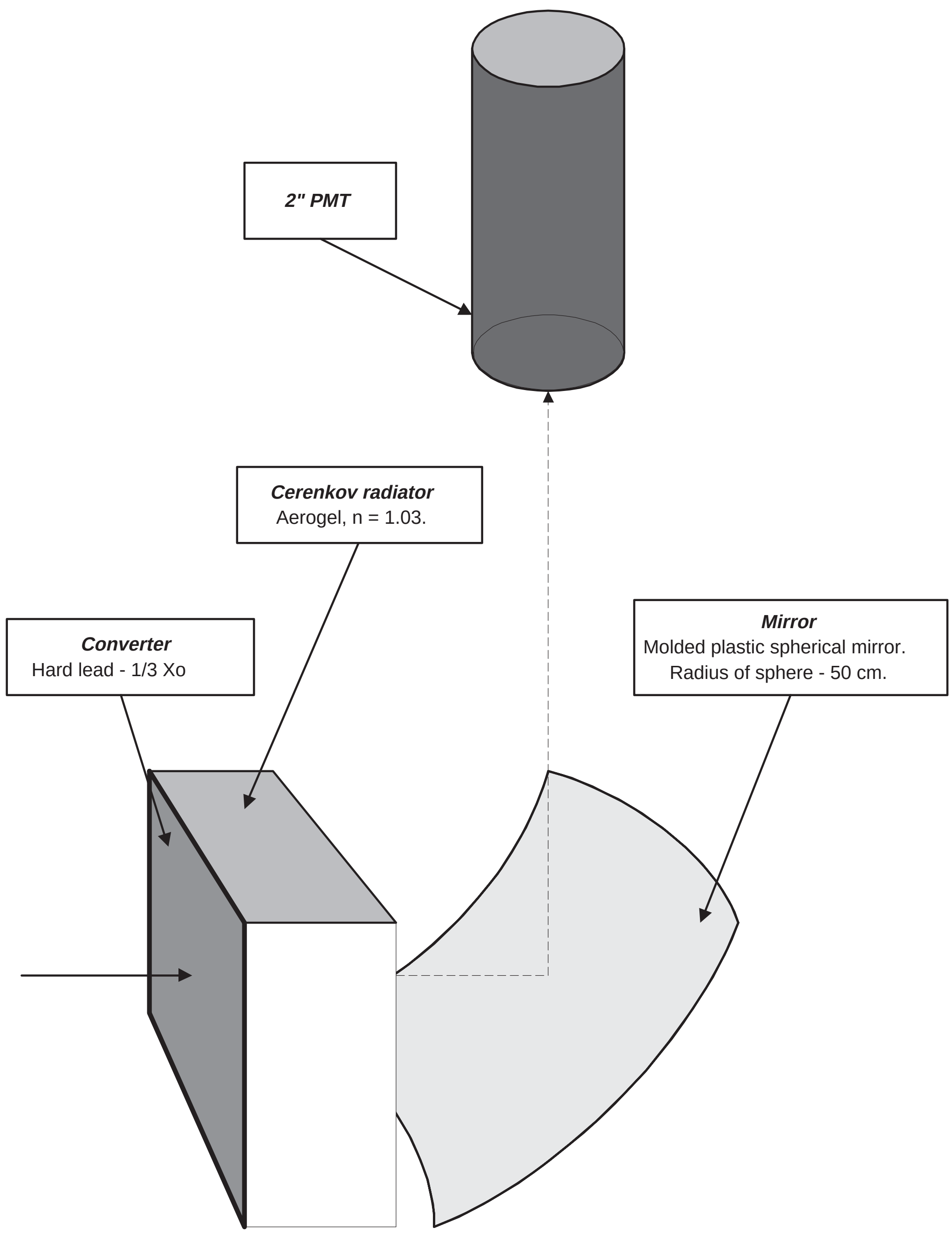
After kinematic cuts, photons into the catcher are mainly stiff

Also, if willing to lose 20% in acceptance **don't need catcher!**





KOPIO Beam Catcher Module

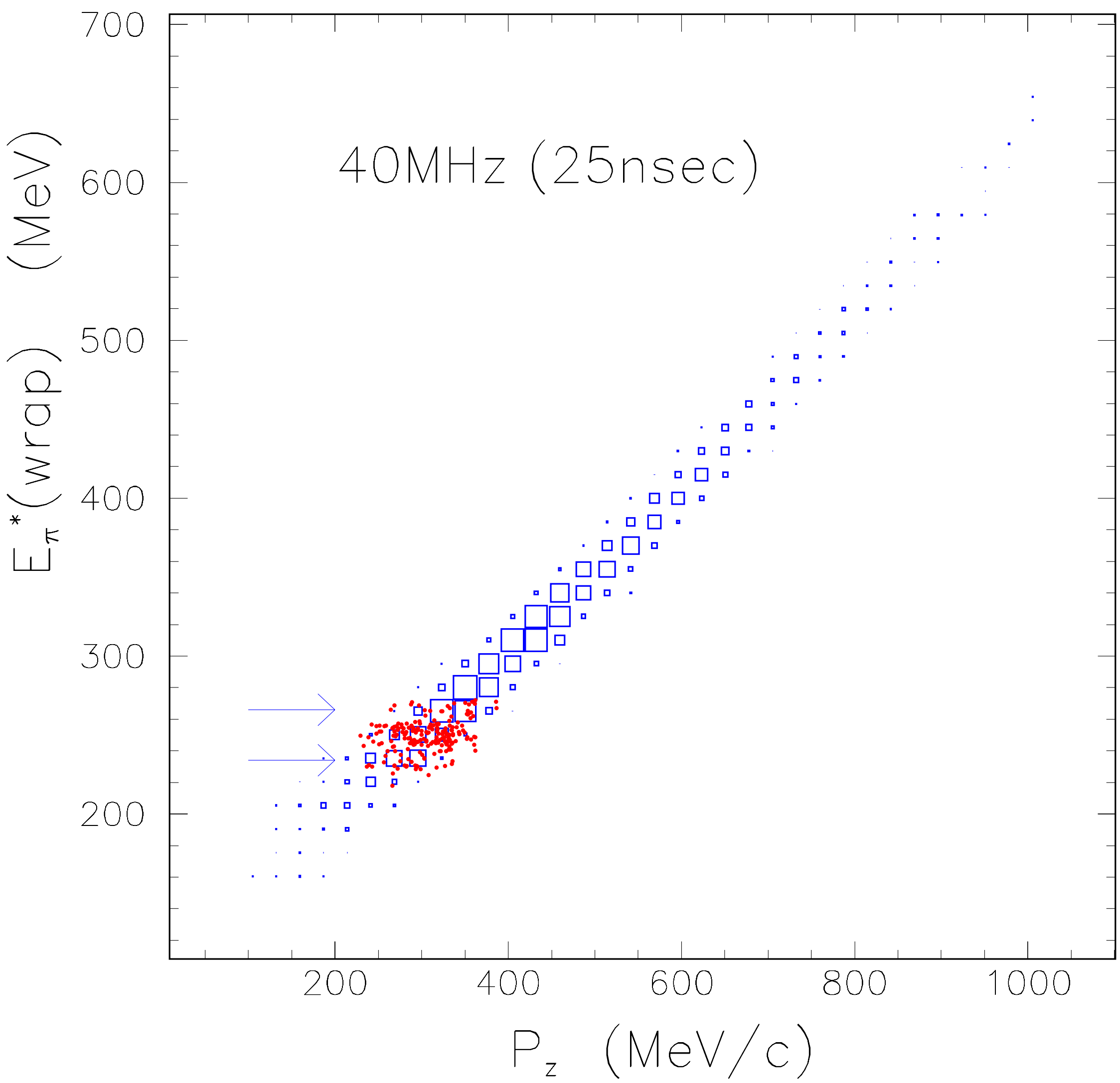


$K\pi2$ wrap-around background

Very slow K_L can wrap into next bucket

In principle can defeat kinematic rejection

In practice, can readily cut them out



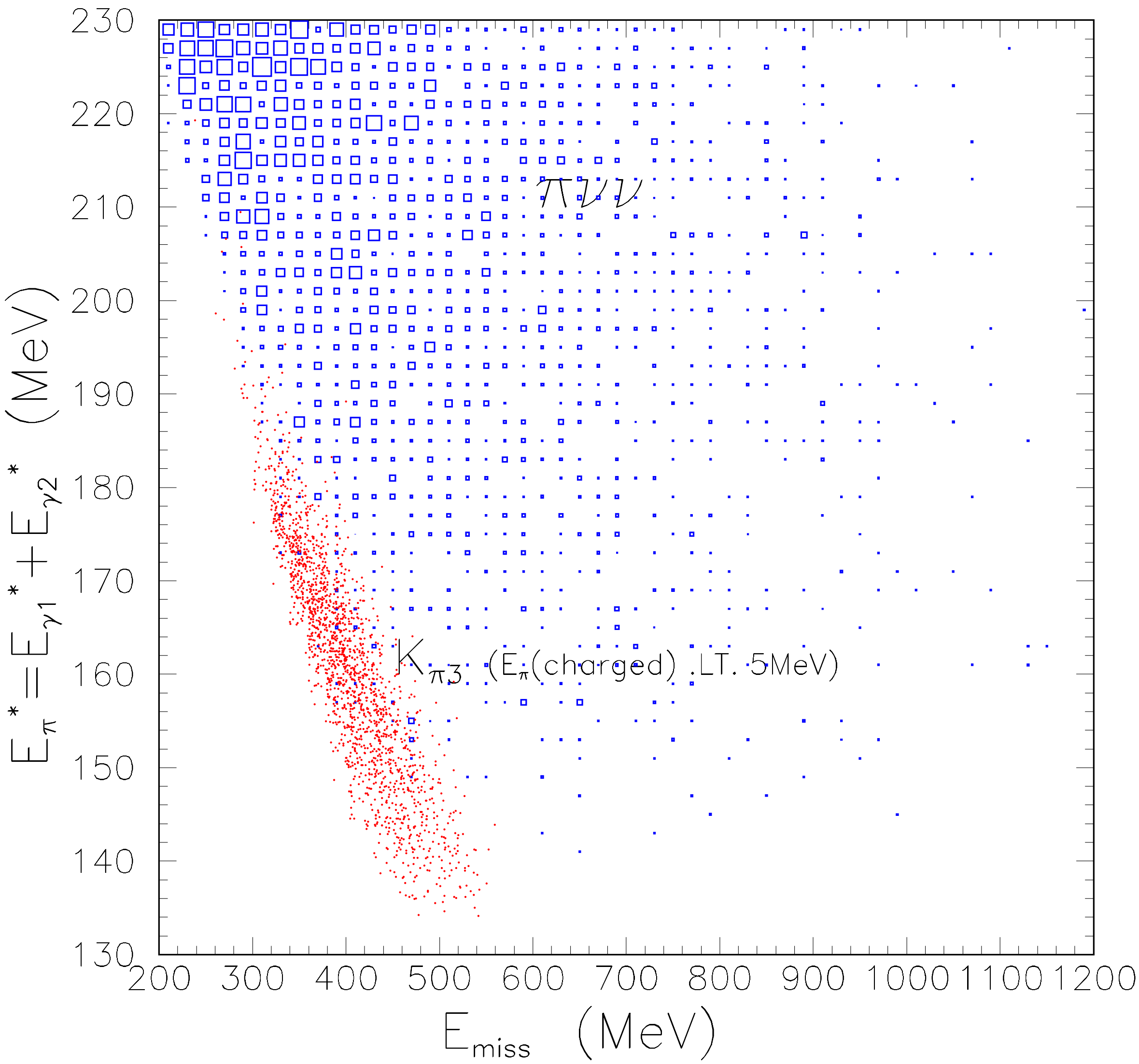
$K\pi3$ background

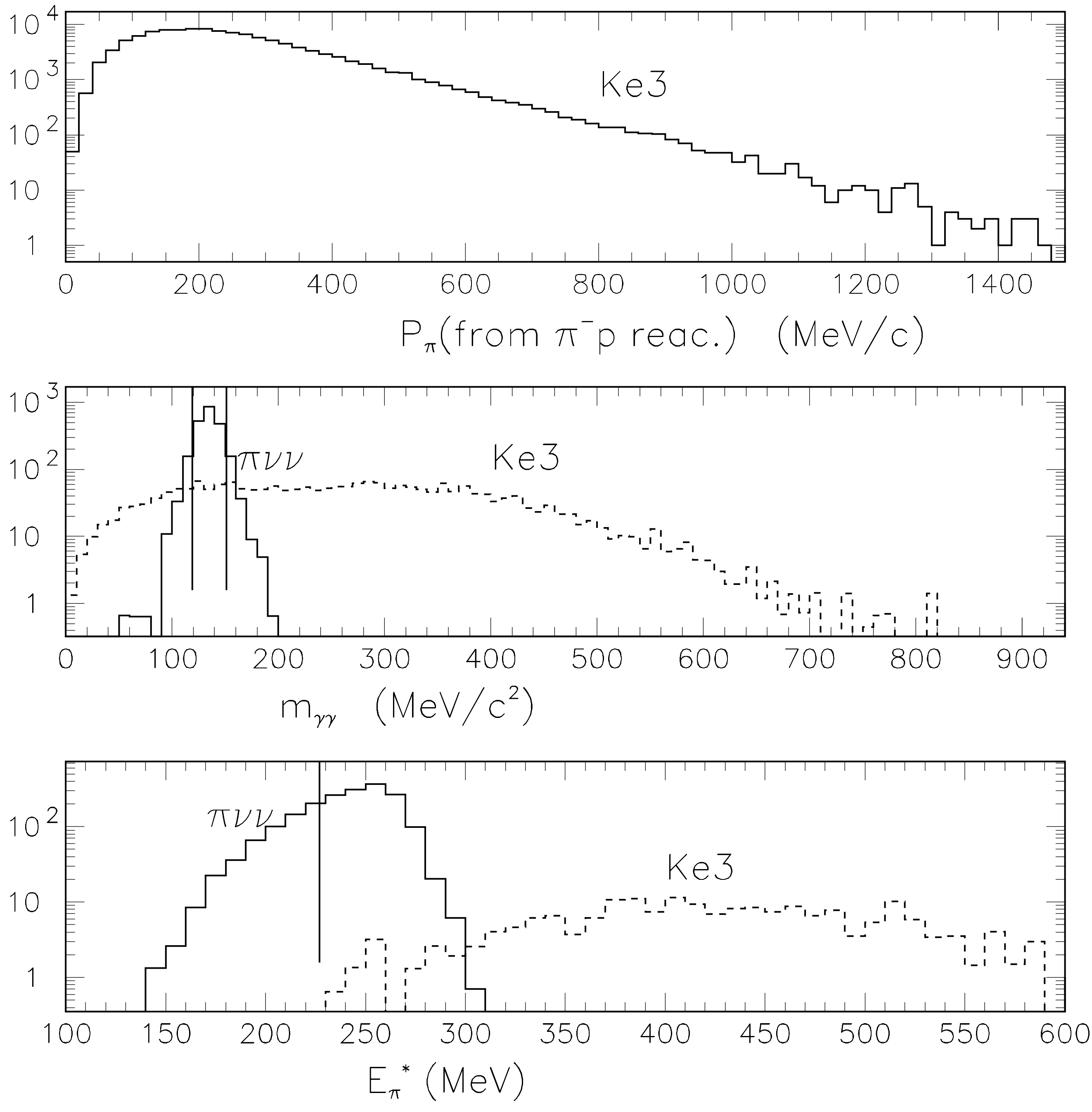
$K_L \to \pi^0\pi^0\pi^0$ not a problem since easy to veto

But $K_L \to \pi^0\pi^+\pi^-$ with slow charged tracks dangerous

Once again kinematics comes to the rescue

Graph shows events with $\pi^\pm$ kinetic energy < 5MeV





Ke3
P_π(from π⁻p reac.) (MeV/c)
πνν
Ke3
m_γγ (MeV/c²)
πνν
Ke3
E_π* (MeV)

Table 13: Estimated event levels for signal and backgrounds.

Process	Modes	Main source	Events
$K_L^0 \to \pi^0 \nu\bar{\nu}$			65
K_L decays ($\bar{\gamma}$)	$\pi^0\pi^0$,$\pi^0\pi^0\pi^0$,$\pi^0\gamma\gamma$	$\pi^0\pi^0$	24
$K_L \to \pi^+\pi^-\pi^0$			9
$K_L \to \gamma\gamma$			0.04
K_L decays ($\overline{charge}$)	$\pi^\pm e^\mp \nu$,$\pi^\pm \mu^\mp \nu$,$\pi^+\pi^-$	$\pi^- e^+ \nu$	0.06
K_L decays ($\bar{\gamma}, \overline{charge}$)	$\pi^\pm l^\mp \nu\gamma$, $\pi^\pm l^\mp \nu \pi^0$,$\pi^+\pi^-\gamma$		0.1
Other particle decays	$\Lambda \to \pi^0 n, K^- \to \pi^-\pi^0, \Sigma^+ \to \pi^0 p$	$\Lambda \to \pi^0 n$	0.03
Interactions	n, K_L, γ	$n \to \pi^0$	0.5
Accidentals	n, K_L, γ	n, K_L, γ	1.5
Total Background			35

be possible to extract η with a precision of approximately 10% from the KOPIO measurement of $K_L^0 \to \pi^0 \nu\bar{\nu}$.

Table 14: Signal/Noise, numbers of $K_L^0 \to \pi^0 \nu\bar{\nu}$ events and the precision of the B($K_L^0 \to \pi^0 \nu\bar{\nu}$) measurement.

S/N	$K_L^0 \to \pi^0 \nu\bar{\nu}$ Signal	B($K_L^0 \to \pi^0 \nu\bar{\nu}$) Precision
1	94	0.15
2	65	0.15
3	48	0.17
5	32	0.20

Conclusions

$K_L \to \pi^0 \nu\bar{\nu}$ is a direct window into CP violation
- best way to determine η
- complementary to B system results

KOPIO designed to collect 65 evts with S:B=2
- or 48 evts with S:B=3, etc.
- can give $7-8\%$ measurement of $Im\lambda_t$

Can explore a window from 2×10^{-9} down to 4×10^{-12}
- only $\sim 2\%$ of which is allowed by S.M.

Very likely to show new physics if such is at work in ϵ'/ϵ

Technique exploits conditions available at AGS
- features highly effective constraints and cross-checks

KOPIO capitalizes on experience (& personnel) of past AGS exps
- E787: similar vetoes, electronics, analysis techniques
- E865: similar rates, calorimetry

Practical, cost effective, solutions for the technical challenges
- vacuum vessel, preradiator, catcher, calorimeter, vetoes

Project cost effective
- AGS running marginal to RHIC
- significant fraction of cap. cost funded by foreign sources